N92-21530

ANNULAR NOZZLE ENGINE TECHNOLOGY

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DRIVER ROCKET SUBSYSTEM

The driver rocket for the combined cycle propulsion system is designed to be compatible with the air augmentation process and to serve as a key element in enabling several of the engine's operating modes: air augmentation, scramjet, and rocket.

For those engines utilizing the on-board air liquifaction process, the rocket subsystem must be capable of operating with liquid air as oxidizer as well as liquid oxygen for the in-space rocket mode.

The power cycle for the driver rocket subsystem could be the simpler and more reliable expander cycle. For cases where more power is required, the gas generator cycle may need to be used.

Annular nozzles are a key element of the rocket driver subsystem.

ANNULAR NOZZLE ENGINE TECHNOLOGY

The annular nozzle concept has been under study since the 1950's. Primary among its advantages is its effective gas expansion in a reduced nozzle length and its better utilization of vehicle base diameter. There are three prominent annular nozzle concepts: the annular bell nozzle, the annular expansion-deflection nozzle, and the Aerospike nozzle. The latter two are obtained respectively from the first through tilting of the throat plane. All three annular nozzles are shorter than the parent and reference circular bell nozzle. They can all be designed to deliver equal flow divergence nozzle efficiency as the circular bell nozzle with the Aerospike nozzle resulting in the shortest length. All three annular nozzle concepts require annular combustors for maximum delivered thrust and therefore require higher coolant flow rates and special design in achieving throat plane thermal stress management.

Extensive effort in design, fabrication and test at Rocketdyne in the years 1955 to 1976 has led to significant advances in the design characterization and utilization of these annular nozzle concepts. The Annular Bell is used in the LANCE missile, 2000 of which have been delivered to the field.

EXPANSION-DEFLECTION NOZZLE

The E-D annular nozzle as it is more commonly referred to has the capability of matching circular-bell design altitude nozzle performance in a nozzle length only 40 percent as long. This nozzle is also capable of providing altitude performance compensation at off-design altitudes through exposure of nozzle base to the prevailing altitude pressure and through gradual recompression on the nozzle surfaces. Seven cold flow models and three hot-firing test configurations have been designed, fabricated and tested at Rocketdyne to characterize the design altitude performance of this concept and its altitude compensating characteristics. Both cryogenic propellants (LOX/H_2) and storable (NTO, UDMH) have been utilized. In addition, the flight characteristics of the nozzle in subsonic and supersonic slipstream have been established. Over 300 tests have been conducted with this concept and numerous design studies completed. A recent design study included a discrete throat area segmented combustor design for the integrated modular engine (IME) concept. Design applications of this concept project high nozzle expansion efficiencies and high combustion efficiencies traceable to the extensive data base for the annular E-D concept. Some performance penalties do accrue for the discrete throat modification.

AEROSPIKE-NOZZLED ENGINE BACKGROUND

Of the annular nozzles, the most extensively studied is the Aerospike. That is because this nozzle concept is capable of the largest savings in length and because altitude compensation and base thrust augmentation features are more pronounced in this nozzle concept. Circular and planar configurations as well as booster and upper stage configurations have been studied and carried from analysis, to design, to fabrication and test. Approximately $100 million was spent from 1960 to 1975 to characterize most operational aspects of these nozzles and their application to missiles, space planes, and the Space Shuttle itself.

AEROSPIKE TESTING

Approximately 260 hot-fire tests and 4800 cold-flow tests have been conducted to characterize design point performance, altitude compensation and base thrust augmentation of the Aerospike Nozzle geometries for optimum expansion performance. Injector geometries to maximize combustion efficiency have been established as well as geometries required for combustion stability of cryogenic as well as storable propellants. Extensive combustor segment testing, full scale uncooled and tubular regenerative cooled nozzle testing has provided a wealth of heat transfer data. From this experience, chamber pressure level and thrust level guidelines for efficient cooling of annular reusable Aerospike configurations has been obtained.

Ideal spike nozzle contours were shown to provide excellent expansion efficiency, altitude compensation was corroborated, and the thrust enhancement from bleed flows into the base was proven. Variations of these characteristics with chamber pressure, propellant type, area ratio and nozzle length were established.

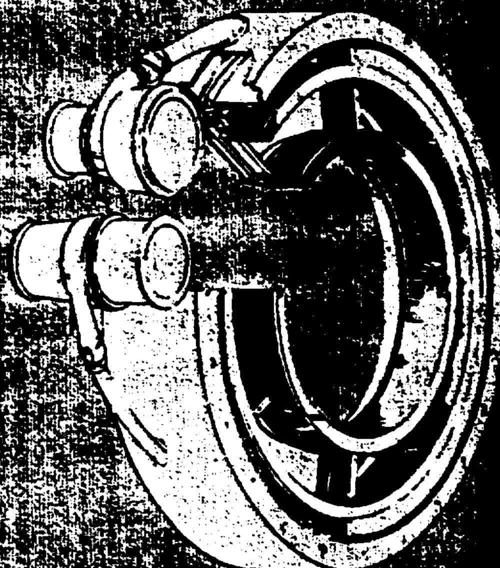
LINEAR AEROSPIKE

One more step in the technology demonstration of the Aerospike concept was the testing of a full-scale planar nozzle engine design with J-2 thrust capability and J-2 engine turbomachinery. This engine configuration demonstrated all ignition, combustion stability, injector performance and thrust chamber cooling required at J-2 system pressure levels. The Aerospike thrust chamber consisted of a channel wall segmented combustion chamber construction with tubular wall spike nozzle attachment. Over 73 tests demonstrated high nozzle efficiency, high combustion efficiency, altitude compensation and hardware durability.

THE COMBINED CYCLE ENGINE

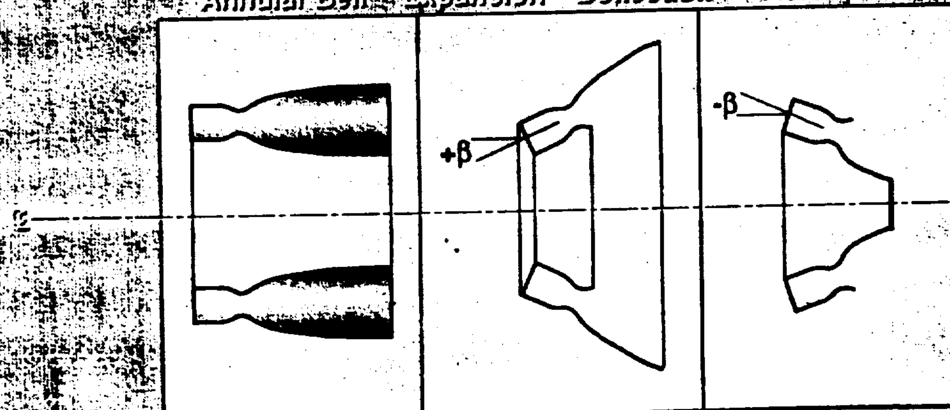
The idea that rocket and airbreathing propulsion can be advantageously combined had been proposed since the early 1950's and found application in missiles such as BOMARC and NAVAJO. More recently the concept of combined-cycle integration of rocket/airbreathing engines (taking advantage of other processes such as ejector, air-augmentation, lace-air cycle, supercharging (fan), recycling (H_2), and afterburning) have been advanced to improve overall performance of the two-stage and single-stage-to-orbit vehicles. Rocketdyne has been active in a large number of these areas. The Annular Nozzle concept in the form of a Bell, E-D, or Aerospike has appeared frequently in the combined-cycle engine designs, especially the supercharged ejector ramjet (SERJ) and the scramlace concepts examined by Marquardt Corporation in the late 1960's. Rocketdyne has explored a number of innovative engine concepts in these areas and contributed its resources and understanding of the advanced nozzle design, fabrication, and test experience. Rocketdyne believes there is a promising potential for application of the advanced annular nozzles to the combined-cycle engine concept.

Driver Rocket for RBCC Engine



- Turbomachinery
  - Hydrogen – high pressure
  - LOX/LAIR – high pressure
  - Zero NPSH oxidizer pump
- Thrust chamber
  - Annular concentric combustors
  - Annular concentric nozzles
  - LOX/LAIR – hydrogen injectors
    - Discrete throat combustors with annular exits
- Power cycle
  - Gas generator (or) expander

Annular Nozzle Concepts



	Annular Bell	Expansion – Deflection	Aerospike
Performance	98.5	98.5	98.5
Length, %	80	40	25
Altitude compensation	Least	Some	Best
Base pressure augmentation	Some	Least	Best

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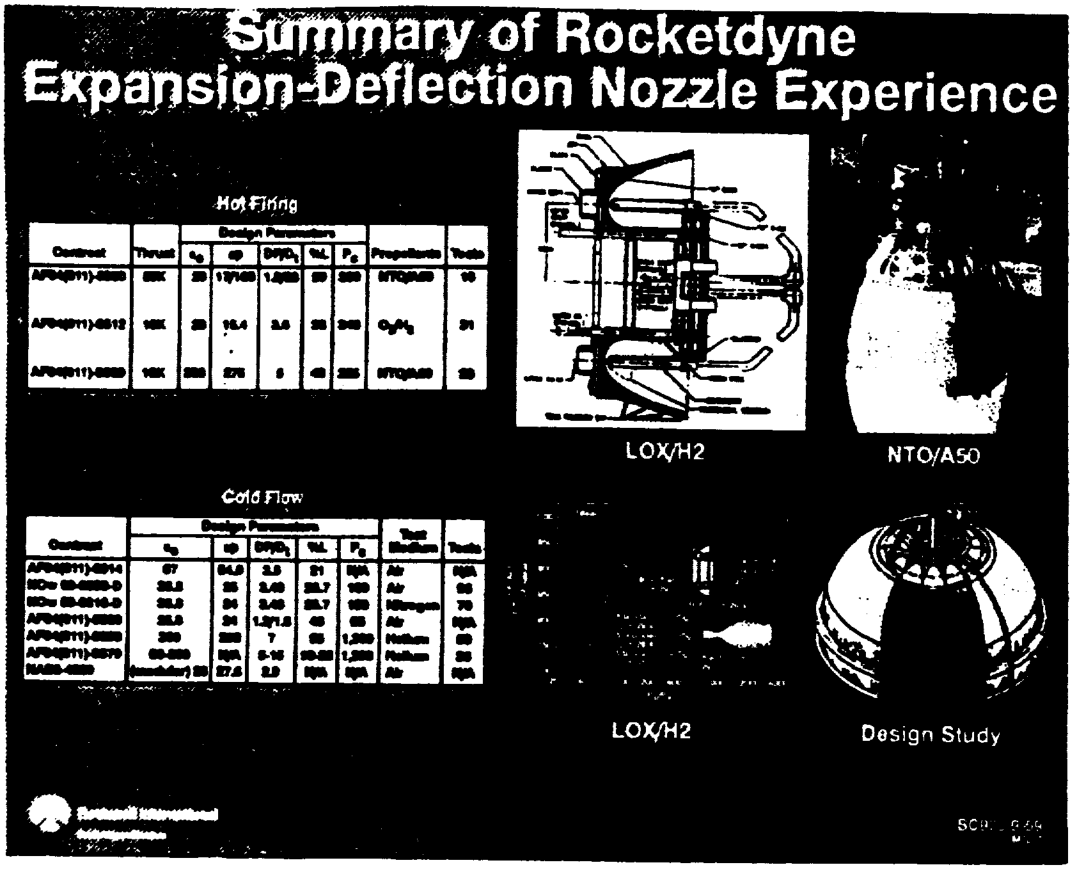

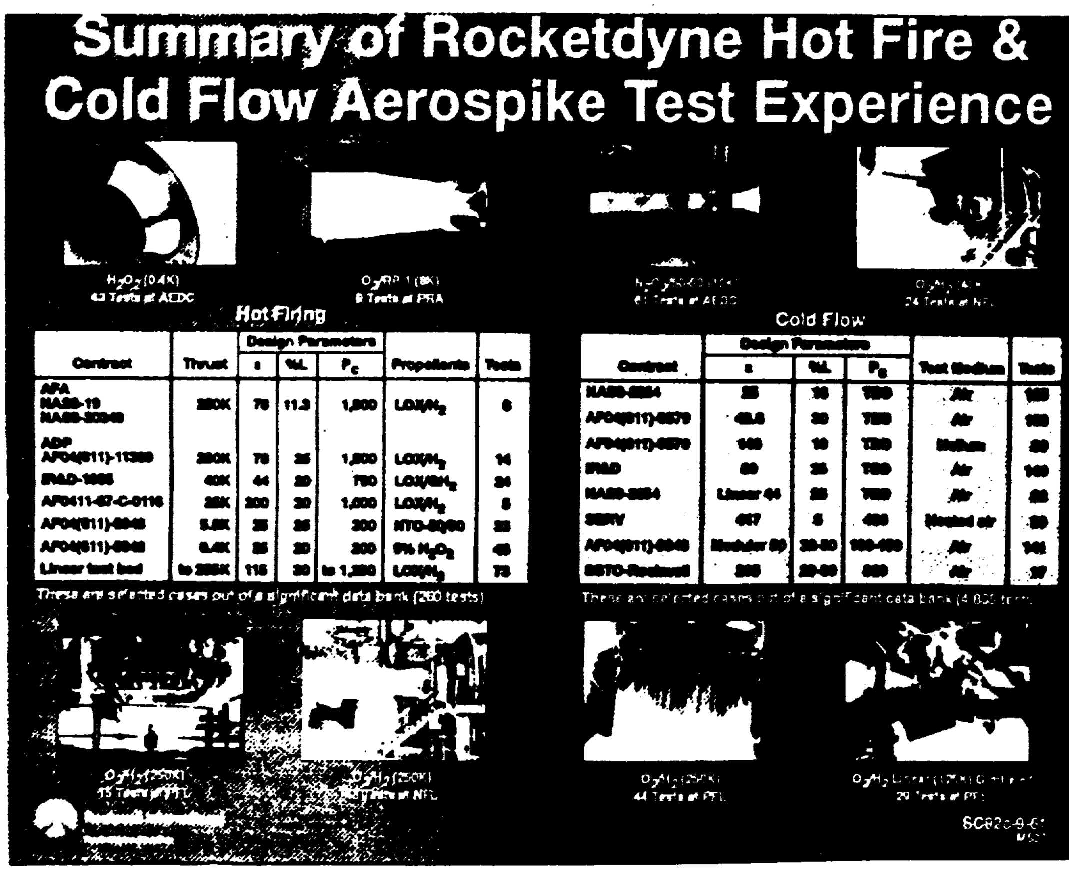

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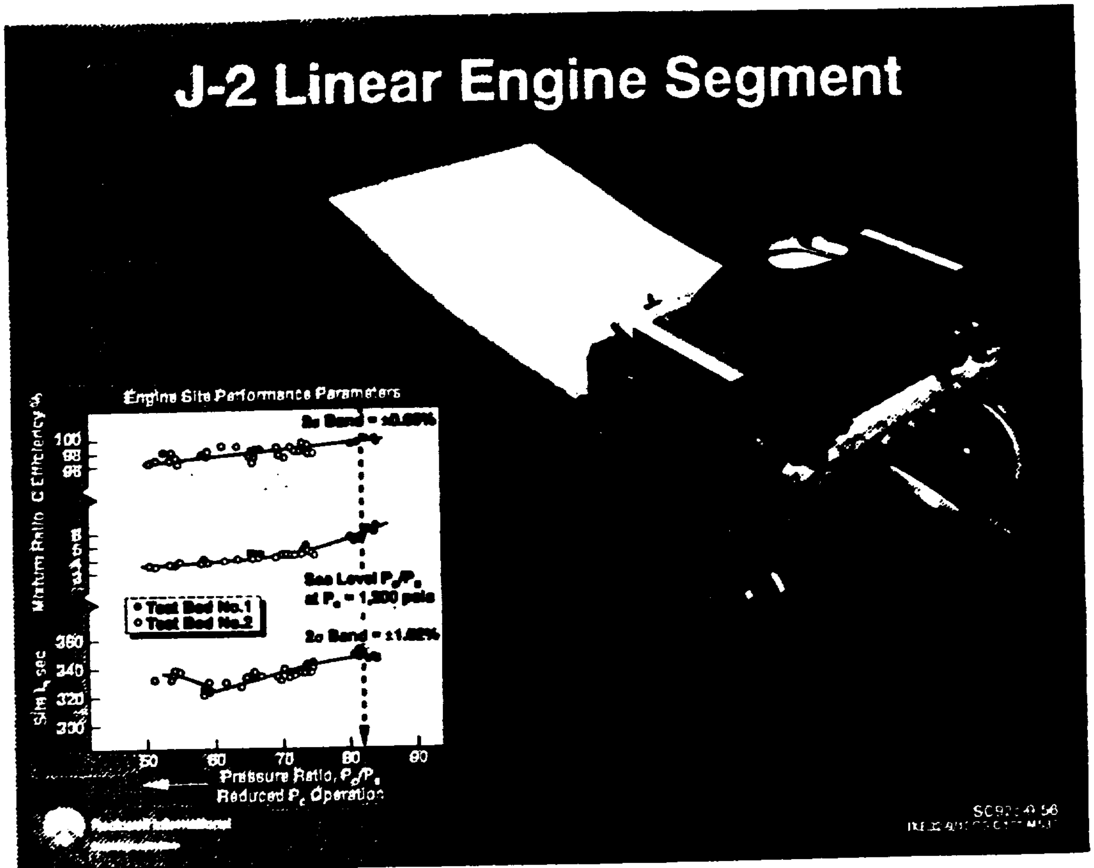
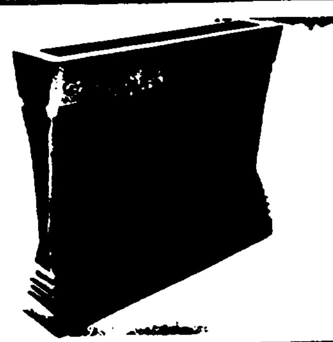
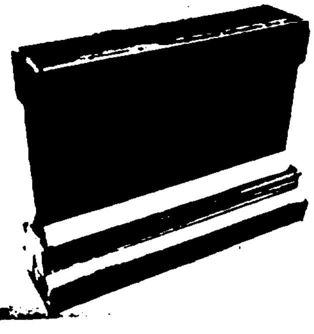




CAST COMBUSTOR SEGMENT LINER

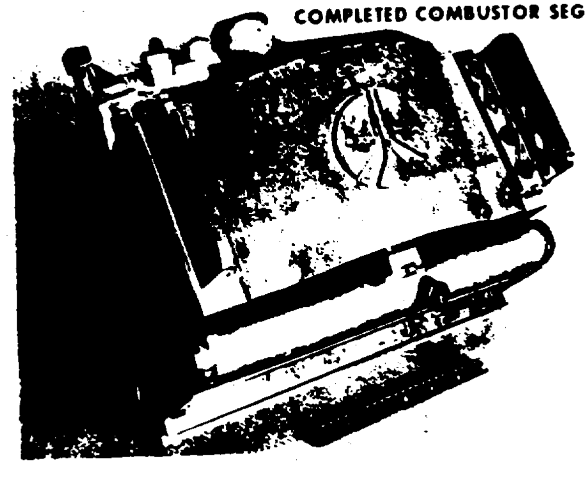
COMBUSTOR SEGMENT SHOWING INJECTOR

thrust chamber —combustor segment



COMBUSTOR SEGMENT WITH ELECTROFORMED CLOSEOUT

COMPLETED COMBUSTOR SEGMENT



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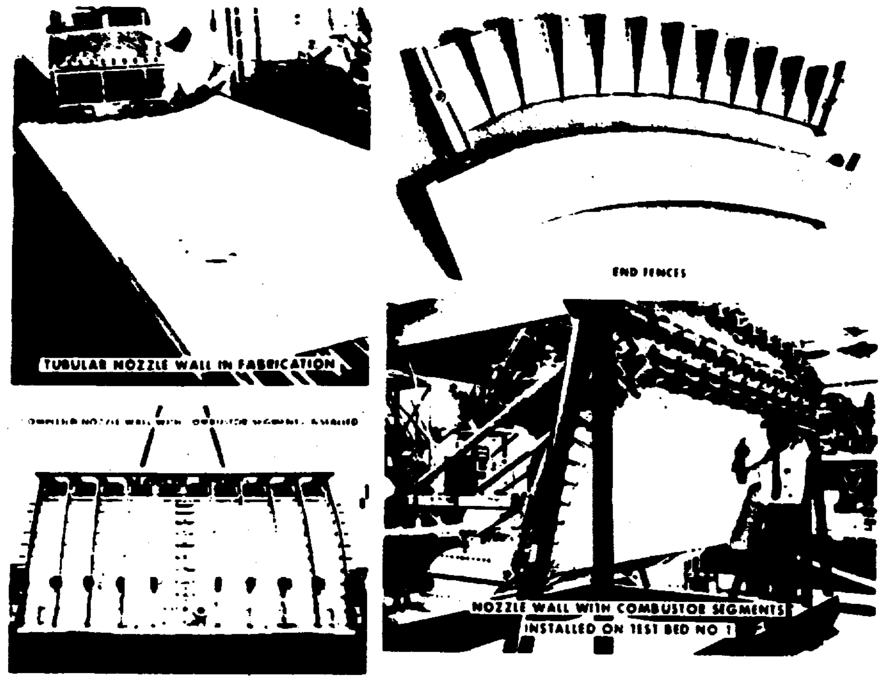
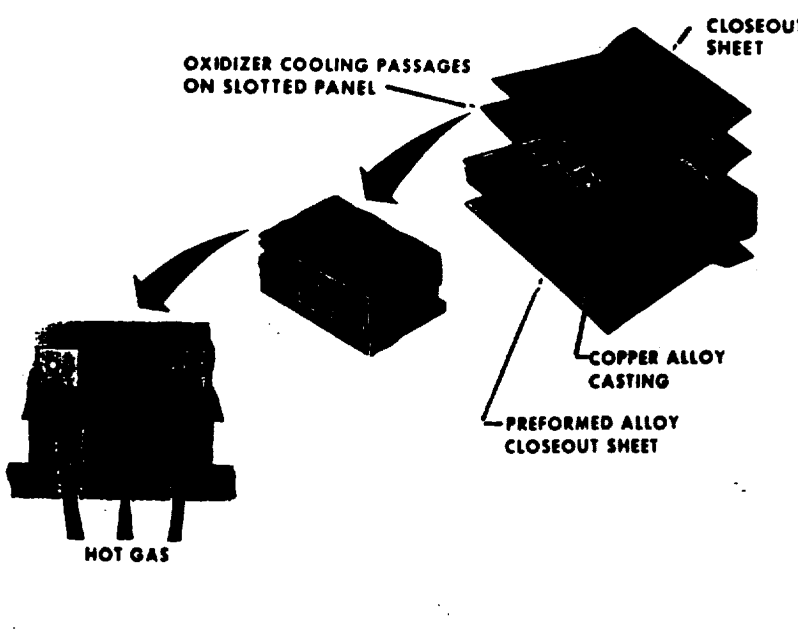
THRUST CHAMBER–NOZZLE ASSEMBLY



DOUBLE PANEL COOLING CONCEPT



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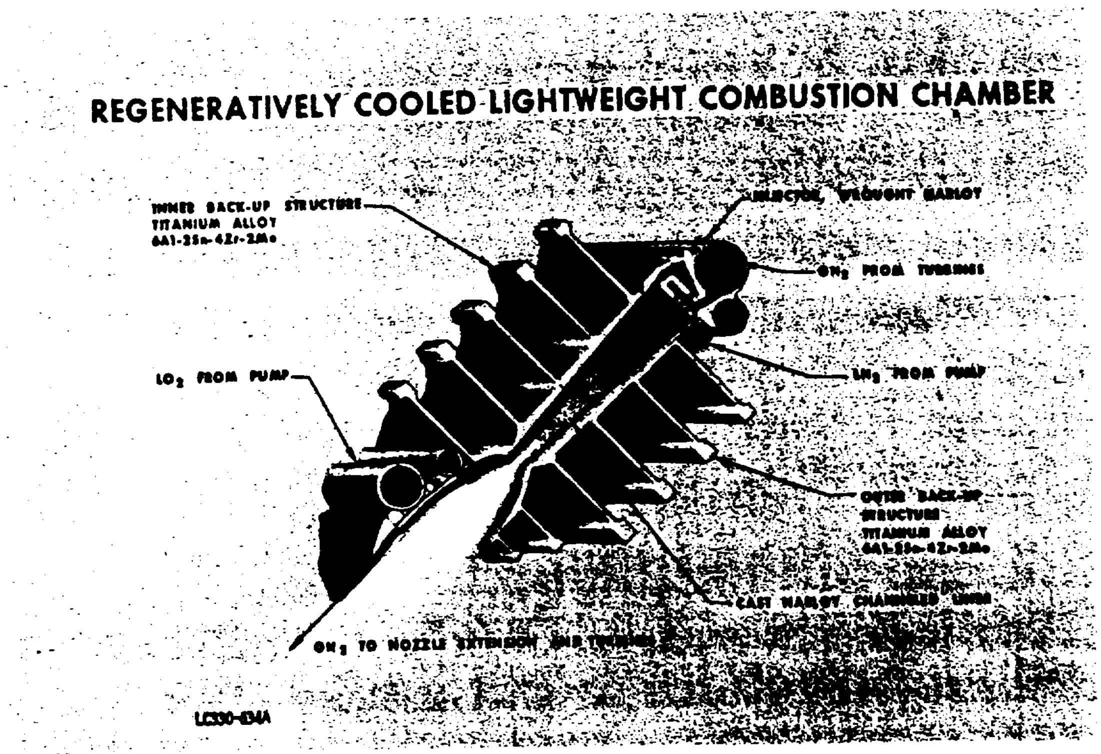

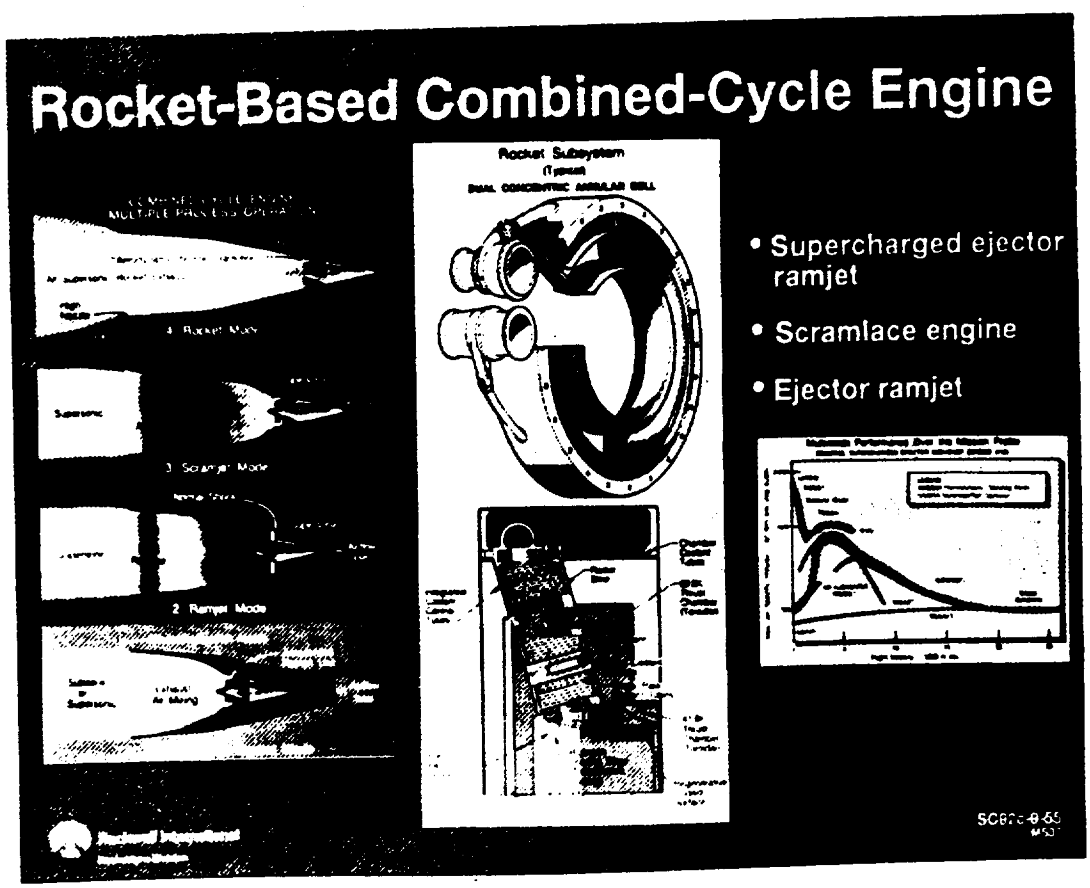

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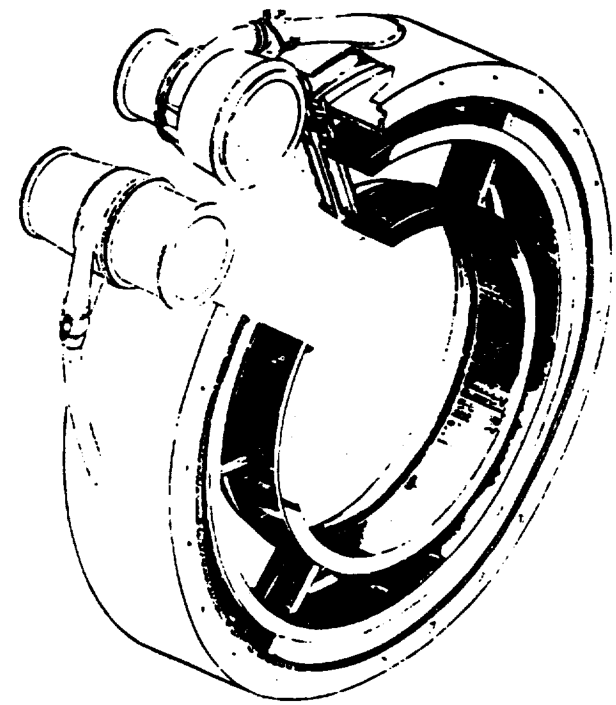
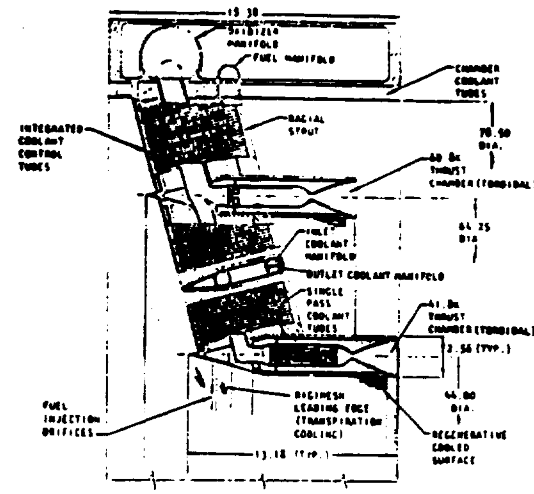
ROCKET SUBSYSTEM (TYP.)

DUAL CONCENTRIC ANNULAR BELL





Jet Compressor R&T (Air Augmented)

F. Herr
Consultant

(Paper Not Received in Time for Printing)